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NUMERICAL MODELLING OF EFFLUENT TRANSPORT IN COASTAL ZONES

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Original scientific paper

Effluent transport in the aquatic environment can be described by using very complex mathematical formulations that include the most relevant processes and their unsteadiness and non-uniformity. This paper gives some evidence of the capability and importance of numerical modelling implementation in the analysis of effluent transport, following the discharge from sewerage submarine outfalls. Numerical models Cormix, Mike 21fm, Mike 3fm and ROMS are described in brief and applied to a particular example in the vicinity of the city of Poreč. Five separate sewerage systems and associated submarine outfalls were encompassed within the numerical model spatial domain: Lanterna, Červar-Porat, Poreč north, Island Sv. Nikola, Poreč south, Petalon i Koversada. Two scenarios of effluent treatment and discharge are modelled that represent the present and the future-planned state according to the development concept project. Positive aspects from the planned activities are obtained through comparison between the faecal coliforms concentration dynamics.

Keywords: *Cormix, Mike 21fm, Mike 3fm, ROMS, numerical modelling, submarine outfall, pollution*

Numeričko modeliranje pronosa zagađenja u morskom akvatoriju

Izvorni znanstveni članak

Pronos oblaka zagađenja u morskim akvatorijima može se opisati izuzetno složenim matematičkim operacijama, koje uključuju veliki broj utjecajnih čimbenika te njihovu nejednolikost i nestacionarnost. U radu su prikazane mogućnosti i važnost korištenja različitih matematičkih modela pomoću kojih se na učinkovit i relativno brz način može dobiti realna slika pronosa zagađenja iz podmorskih ispusta. Opisani su sofisticirani matematički modeli Cormix, Mike 21fm, Mike 3fm i ROMS, uz prikaz njihove primjene na konkretnom primjeru. Odabrano je područje Poreštine uz ispitivanje utjecaja podmorskih ispusta sustava javne odvodnje Lanterna, Červar-Porat, Poreč sjever, Otok Sv. Nikola, Poreč jug, Petalon i Koversada, na promjene stanja u morskom akvatoriju šireg područja. Razmatrana su dva slučaja, od kojih se prvi odnosi na sadašnji stupanj izgrađenosti sustava odvodnje, a drugi uključuje sve planske promjene prema usvojenoj koncepciji razvoja. Kao osnovni pokazatelj kakvoće vode u efluentu usvojena je koncentracija fekalnih koliforma. Dodatno je razmatran i utjecaj biološke razgradnje organske tvari.

Ključne riječi: *Cormix, Mike 21fm, Mike 3fm, ROMS, numeričko modeliranje, podmorski ispust, zagađenje*

1 Introduction
Uvod

The basics of the hydrodynamics of pollution discharge in the sea are: advection convective dispersion, and turbulent diffusion [1]. The above processes are characterized by mixing of internal energy and mass of dissolved or suspended matter, and the one-dimensional approach cannot be applied to represent reality [2].

The analysis of pollution discharge from submarine outfalls requires a combination of physical, chemical and biological processes. This results in efforts to develop numerical models that include all three processes [3].

Modelling of pollution discharge in marine aquatories cannot be based on constant parameters, but requires simulations in representative time periods, including temporally variable parameters. Such parameters include aspects of the pollution outflow, sea temperature, salinity, as well as changes of light intensity and movement of sea currents [4, 5].

In the analysis of pollution introduced into the sea through the diffuser part of the submarine outfall, the influence of factors in the wider spatial domain may also change. Therefore, the space is usually divided into near-field and far-field zones [4]. The near-field zone covers the space near the diffuser, characterized by upward flow dominated by the influence of the discharge rate and difference of densities of pollution and sea water. Further, a buoyant lifting plume is formed, that is influenced by density difference and sea stream velocity [6] and typically reaches the horizontal barrier (pycnocline layer), at which the plume enters the far-field zone and propagates in the direction of prevailing ocean currents [7].

Concentrations in the pollution plume at the end of the near-field zone, defined by some adequate model specialized for the analysis in the near-field zone, may be used for initiating of pollution field in the numeric 2D or 3D models, which are further used in the analysis of discharge in the far-field zone. This approach avoids very dense calculation network in 2D or 3D numerical models in the near-field zone.

This paper presents an example of integrated numerical modelling of pollution discharge in several spatial and temporal levels through establishing of the model system continuously linked to most important properties of hydraulic characteristics of outflow from submarine outfalls and dynamics of the surrounding ocean. The analysis was concerned with the interaction of several submarine outfalls of public sewerage in the area of Poreč – sub-systems Lanterna, Červar-Porat, Poreč North, Island Sv. Nikola, Poreč South, Petalon and Koversada. The numerical models used in the numerical analyses were Cormix, Mike 21fm, Mike 3fm and ROMS. Two cases were analyzed – the present status of development when each system has a submarine outfall, and the planned future development which includes connecting of the minor systems Červar-Porat, Island Sv. Nikola and Koversada to neighbouring larger systems. The results of the analysis indicate potential reduction of pollution concentration in the zone meant for sports and recreation (300 m from shoreline) provided the planned works are implemented. The basic index of water quality in relation to pollution is the concentration of faecal coliforms. The numerical analyses also take into account biological decomposition.

2 Numerical models
Numerički modeli

The following text will present and describe some of the basic models of numerical modelling that may be successfully applied in realistic presentation of pollution discharge in marine aquatories. The models presented here have also been used in the particular case of analysis of the interaction of several submarine outfalls of public sewerage in the area of Poreč.

2.1 Model Cormix

The Model Cormix is generally used to describe the discharge of pollution into the surrounding recipient ocean on the basis of characteristic scales or lengths. In modelling of pollution discharges on submarine outfalls the model takes into account the construction solutions characteristics of the diffuser section. Based on the dimensional analysis, ocean current is divided in sections or lengths where the characteristic regime of ocean current is observed. Dimensional analysis offers the solutions for each of these regimes, and the set of characteristic lengths determines the point of transition between individual ocean current regimes.

The integrated model Cormix analyzes the discharge of the total field of mass, momentum and internal energy, relying on the hypothesis of proportionality of velocities of drawing in of the recipient liquid (sea water) into the lift jet and the velocities on the central streamline of the upward jet. Regardless of the formulation and description of turbulence, this model also contains coefficients taken from the results of experimental measuring. In the analysis of dilution in the near-field zone Cormix takes into account the influence of forced ocean current of the recipient (sea water) and the surrounding ocean current at the point of introduction. Along the vertical of the sea column, uniform ocean current velocity is assumed.

2.2 Model Mike 3fm

The Mike 3fm model system is based on flexible discrimination approach, and its hydrodynamic (HD) module solves numerically the 3D Reynolds equations with Boussinesq assumption and the assumption of hydrostatic pressure. The sea level is taken through the sigma-coordinate approach. For discretization of equations, the method of final volumes is used, based on a single cell and discretization of continuum into non-overlapping elements. In the horizontal direction, non-structured discretization is used, and in the vertical direction, structured discretization. For calculation of convective flow, an approximate Riemann's solver [8] is used, which allows calculation also in cases of discontinuous solutions. In temporal integration, the approach is used where horizontal parameters are treated explicitly, and vertical ones implicitly. The turbulence module uses k-ε formulation [9] in vertical direction, and the Smagorinsky concept in horizontal direction.

2.3 Model Mike 21fm

The numerical model Mike 21fm solves in two dimensions (in the horizontal plane) stationary/ non-stationary flow of incompressible liquid, and convective dispersive process of discharge of dissolved or suspended matter in one vertical homogenous layer, under the assumption of hydrostatic distribution of pressure. The model system of shallow fluid equations contains vertically integrated continuity equations, preservation of quantity of movement and convective-dispersive discharge [10, 11].

For spatial discretization the model uses continuous and non-overlapped triangular elements (final volumes), and the model spatial domain is therefore covered by an unstructured mesh network [12, 13, 14]. Horizontal convective members are calculated by using the Riemann's solver with Roe's approximation [8, 15].

2.4 Model ROMS

Spatial domain of the model ROMS covers the area of the entire Adriatic Sea, and the recommendation is to use high horizontal resolution of 2 km, which allows realistic inclusion of relevant river basins into the Adriatic Sea. For the purpose of modelling of natural processes optimum open boundary conditions for tidal dynamics have been included in the manner described in [16]. The influences of 28 inflows in the eastern and western sides of the Adriatic are included in the model ROMS with scaled daily averaged climatological values of discharges and temperatures according to [17]. Salinity of all inflows is parameterized with the value of 0 PSU. Also, to insure positive defining of these parameters, advanced option "upwind" of third order was used. The ROMS model, according to the structure of numeric scheme is a model of final differences with free sea level, vertical coordinate following bathymetry, based on hydrostatic, Boussinesq primitive equations [18].

2.5 Atmospheric model ALADIN
Atmosferski model ALADIN

For atmospheric forcing of the numerical models ROMS and Mike 3fm, the results of a local atmospheric forecast model ALADIN were used, with spatial resolution of 8 km and time resolution of 3 hours. Bulk relation formulae were used, which requires wind, air pressure, air temperature, relative humidity, cloudiness, rainfall and short-wave radiation.

The ALADIN model (Aire Limitee Adaptation dinamique et Development InterNational) is hydrostatic and based on the primitive equations and the numeric implementation is carried out in cooperation with several national meteorological institutions. The model results from the global ARPEGE (Action de Recherche Petite Echelle Grande Echelle) model of Meteo-France [19], with mutual exchange of data on most relevant physical parameters [20]. The main difference in using in limited areas is that Fourier's transformation is carried out in both directions with the expansion zone providing periodicity [21]. The Croatian version of the operating mode ALADIN is carried out in the spatial domain covering the territory of Croatia with the Adriatic and orography of the Alps, Dinarides and Apennines [22].

3
Analysis of the problem
Analiza problema

In the Poreč coastal zone there are several public sewerage systems in operation: Lanterna, Červar-Porat, Poreč North, Island Sv. Nikola, Poreč South, Petalon and Koversada. All systems are equipped with the pre-treatment stage (mechanical pre-treatment). In accordance with the future concept, the systems Červar-Porat and Island Sv. Nikola are to be connected to the system Poreč North, and the system Koversada to Petalon. As an alternative solution, second stage of treatment (biological treatment) is considered, with reduction of the initial emission of pollution concentration into the sea by approximately 95 percent.

In order to determine the required level of treatment on planned sewage treatment plants, numeric analysis of pollution propagation from submarine outfalls was carried out, for the present level of development and subsequently for alternative solutions of the future status. The numeric analysis was done with model Cormix in the near-field zone, and with model Mike 21fm in the far-field zone. The parameters of concentration and mass flow in the pollution plume at the end of the near-field zone, calculated by model Cormix were used for initiation of pollution sources in the two-dimensional model of convective dispersion Mike 21fm. As the stream field in the coastal zone of Northern Adriatic is under the influence of the dynamics of the open sea [23], for marginal conditions on the open borders of model Mike 21fm extracted stream velocities were used, obtained by 3D numerical model Mike 3fm, which covers the wider area of the Istrian costal zone. This encompasses also the influence of the open sea on streams in the coastal zone of the Istrian west coast. Further, in defining of marginal conditions of spatial and temporal dynamics of salinity, temperature and sea level in open borders of model Mike 3fm, the values were used which were obtained by the numerical model ROMS, which covers the entire area of the Adriatic [23].

The model spatial domain in the analysis of hydrodynamics and propagation of pollution, carried out with model Mike 21fm, covers the coastal zone from the entrance into Limski Channel in the south to the town of Novigrad in the north. The choice of such wider area encompasses the analysis of interaction between pollution plumes created by the operation of all existing and planned public sewerage outfalls in the given marine coastal zone.

The analysis of pollution discharge in the area of the near-field and far-field zone is carried out under the hypothetic assumption of absence of stratification (vertically homogenous column of sea density), which results in free lifting of the pollution plume to sea surface. This describes the "worst case scenario" for the summer period, at eventual occurrence of transient conditions in the atmosphere, with winds of high intensity and homogenizing of densities along the sea column vertical.

3.1
Spatial domains of numerical models
Prostorne domene numeričkih modela

The entire area of the Adriatic Sea represents the spatial domain used in numerical analyses conducted with the model ROMS. Fig. 1 presents the position of the spatial domain of model Mike 3fm incorporated in model ROMS. Fig. 1 shows spatial discretization of the domain of model Mike 3fm with triangular final volumes. In the horizontal direction, spatial discretization was used with variable spatial spacing between numeric nodes of minimum 100 m in the coastal area to maximum 2000 m in the open sea. In the vertical direction, 20 sigma layers were used.

In the area of the spatial domain of model Mike 3fm, there are two ADCP current gauging stations, S1 and S2 (Fig. 1), which were the basis for verification of model results. The results of model ROMS were also verified on the basis of measured vertical profiles of sea salinity and temperature on 75 CTD stations situated along the east coast of the Adriatic [23].

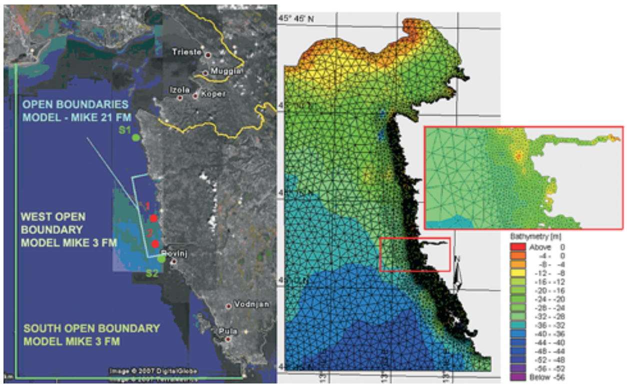

Figure 1 Spatial domain of model Mike 3fm (red lines – open borders of model Mike 3fm) in the model of the entire Adriatic (ROMS), with positions of ADCP and CTD gauging stations, and discretization with non-structured network of final volumes.
Slika 1. Prostorna domena modela Mike 3fm (crvene linije – otvorene granice modela Mike 3mm) u model cijelog Jadrana (ROMS) s pozicijama mjernih ADCP i CTD postaja i diskretizacija s nestrukturiranom mrežom konačnih volumena

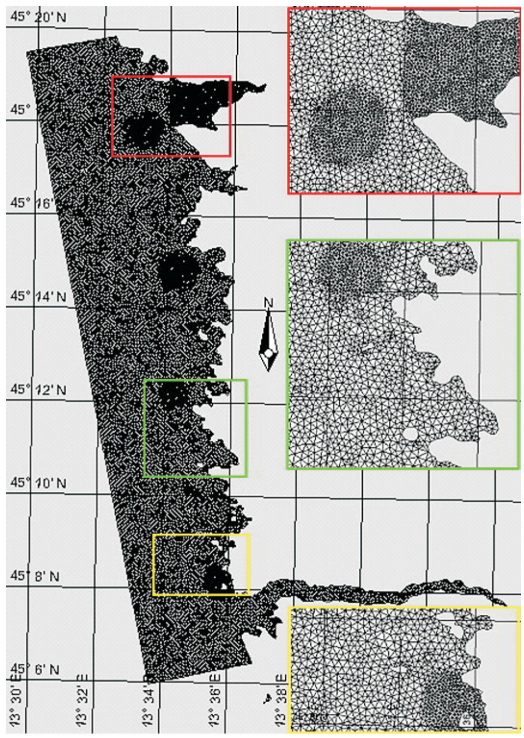

Figure 2 Discretization of spatial domain of model Mike 21fm with non-structured network of final volumes.
Slika 2. Diskretizacija prostorne domene modela Mike 21fm s nestrukturiranom mrežom konačnih volumen

Fig. 2 gives a detailed insight into discretization of the spatial domain of model Mike 21fm with final volumes. In the vicinity of diffusers of submarine outfalls the spacing between numeric nodes is approximately constant, with the value of 30 m. In the remaining part of the spatial domain, distances between numeric nodes are variable, ranging from 10 to 1000 m.

3.2
Analysis of submarine outfalls
Analiza podmorskih ispusta

The basic hydraulic characteristics of analyzed submarine outfalls Lanterna, Červar-Porat, Poreč North, Island Sv. Nikola, Poreč South, Petalon and Koversada, or of their respective diffusers are defined by existing diffuser lengths L_{dif}. Analyzed value of inflow discharge through the submarine outfall pipe refers to maximum hourly discharges in outfall pipes Q=$Q_{max.h}$. In the cases of outfalls Červar-Porat, Island Sv. Nikola and Petalon diffuser section has not been constructed. Tab. 1 shows the existing diffuser lengths and corresponding actual and planned maximum hourly discharges of wastewater.

Table 1 *Basic properties of submarine outfalls*
Tablica 1. *Osnovna obilježja podmorskih ispusta*

System	$L_{outfall}$/m	L_{dif}/m	$Q_{max.h}$/m^3/h	
			present	planned
Lanterna	466	120	0,1	0,1
Červar-Porat	300	0	0,006	dismissed
Poreč North	806	194	0,108	0,165
Island Sv. Nikola	300	0	0,002	dismissed
Poreč South	806	194	0,14	0,186
Petalon	455	0	0,077	0,077
Koversada	110	0	0,003	dismissed

L_{dif} - length of submarine outfall diffuser section, m
$L_{outfall}$ - length of submarine outfall pipe from mainland to diffuser, m
$Q_{maks.h}$ - maximum hourly discharge in submarine outfall pipe, m^3/h.

In order to achieve as realistic description as possible of introduction of pollution into the surrounding environment, submarine outfall operation with time varying inflow was used. Fig. 3 shows the variation of inflow discharge during the summer period, for the case when the design value of hourly discharge in the sewerage system is 100 l/h.

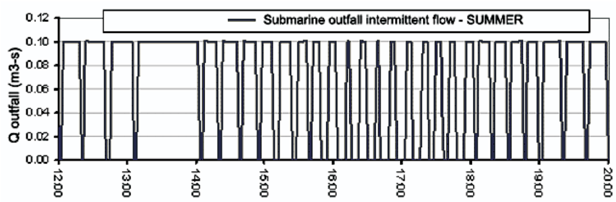

Figure 3 *Dynamics of operation pulses of submarine outfall with design inflow discharge* $Q_{outfall}$ = 0,1 m^3/h *in the period of* 12 *to* 20 h *during a typical summer day.*
Slika 3. *Prikaz dinamike pulseva rada podmorskog ispusta s projektiranom vrijednosti protoka upuštanja* $Q_{outfall}$ = 0,1 m^3/h *u periodu od* 12 *do* 20 h *za vrijeme karakterističnog ljetnog dana*

For analyzed public sewerage systems with second stage treatment, at the point of pollution introduction into the sea the initial concentration used was 107 FK/100 ml [24], and in the case of third stage of treatment, 105 FK/100 ml.

3.3
Parameters of physical oceanography used
Korišteni parametri fizikalne oceanografije

The analysis of pollution propagation in near-field zones (model Cormix) requires knowledge of the surrounding physical oceanographic conditions, primarily the vertical distribution of current $V(z)$ and the sea density $\rho_m(z)$. Vertical density profiles used here were measured by CTD probes on oceanographic stations 1 and 2 in the vicinity of planned positions of submarine outfall diffusers (Fig. 1). Stream velocities at planned positions of submarine outfall diffusers were obtained from the results of the numerical model Mike 3fm.

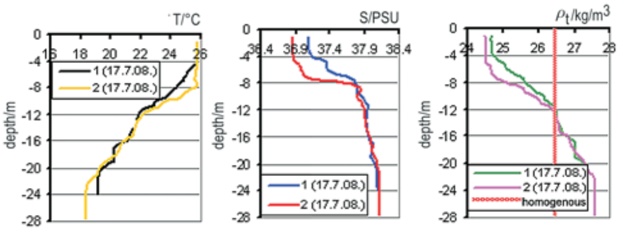

Figure 4 *Measured vertical profiles of temperature, salinity and reduced sea density on CTD stations.*
Slika 4. *Izmjereni vertikalni profili temperature, saliniteta i reducirane gustoće mora na CTD postajama*

Measuring of profiles of temperature, salinity and reduced densities on CTD stations 1 and 2 in the period of 17.07.2008., indicated presence of stratification (Fig. 4). As mentioned earlier, numerical analysis is conducted for the hypothetic scenario in which sea density is vertically homogenous. The estimate accepts the value of 1026,45 kg/m^3, which corresponds to mean values of measured densities at the vertical CTD stations (Fig. 4).

Propagation of the pollution plume in the far-field zone, after rising to the sea surface, is monitored by the model Mike 21fm. Generating of the ocean current field in the model Mike 21fm is achieved by using non-stationary and non-uniform velocity profiles on open boundaries (marginal condition of model Mike 21fm, Fig. 1). These velocity profiles are based on the results of 3D model Mike 3fm. Thus, model Mike 21fm monitors spatial dynamics of the pollution plume in the horizontal layer of constant depth of 1 m.

In the analysis of dynamics of concentration of faecal coliforms, in model Mike 21fm the accepted values of bacteria decay were T_{90} = 6,8 h. During the night, bacterial decay is considerably slower, and the calculated value was T_{90} = 33 h.

3.4
Model calibration
Kalibracija modela

In the calibration of results of the numerical model ROMS, the results were used obtained within the frame of the scientific project "Monitoring of the Condition of the Adriatic Sea", carried out in the territorial sea of the

Republic of Croatia [23]. The results of the ROMS model, using improved physical processes, were compared with the available CTD measurements and additionally with surface temperature fields for the entire Adriatic. The model used 30 vertical S-levels, adequately describing processes in the surface layer, which makes the comparison with surface temperature fields obtained by satellite considerably more successful.

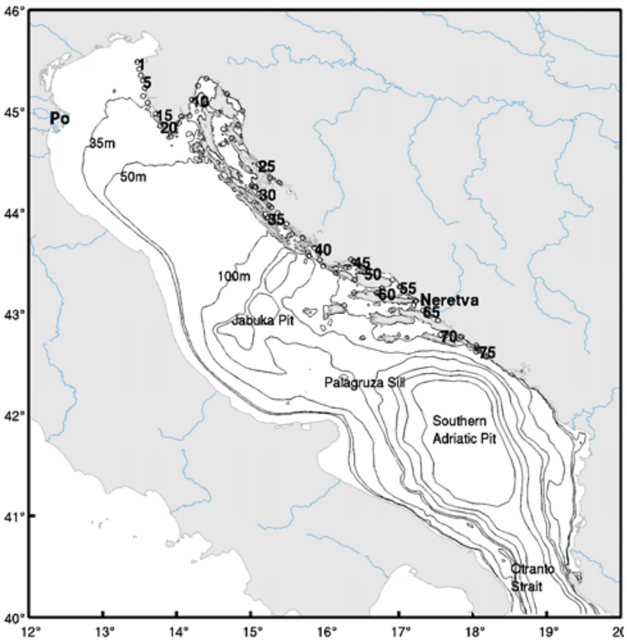

Figure 5 *Placement of CTD stations for measuring of temperature, salinity and density*
Slika 5. *Prostorni raspored mjernih CTD postaja za mjerenje temperatura, saliniteta i gustoća*

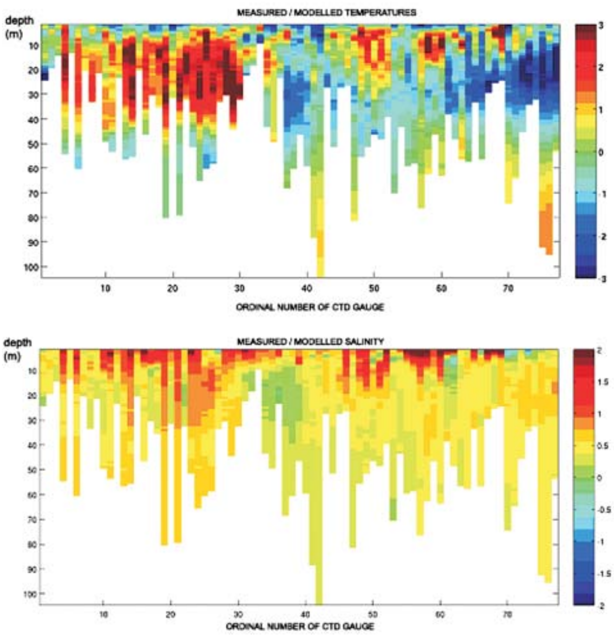

Figure 6 *Difference of measured and model (ROMS) values (MEASURED - MODEL) for temperature (up) and salinity (down) on verticals of CTD measuring stations (July, 2008)*
Slika 6. *Prikaz razlika izmjerenih i modelskih (ROMS) vrijednosti (MJERENO - MODELIRANO) za temperaturu (gore) i salinitet (dolje) na vertikalama CTD mjernih postaja (mjesec srpanj 2008.)*

During numeric simulations, the results obtained with the model ROMS were compared with CTD measurements in July, 2008. Positions of CTD stations are shown in Fig. 5. Station numbers were determined by arraying the stations from north to south. Deviations of model values of temperature and salinity from those measured on CTD station profiles from Fig. 5 for July are shown in Fig. 6.

Calibration of model Mike 3fm was carried out with reference to results of measuring with ADCP velocity gauges at stations S1 and S2 (Fig. 1). Fig. 7 and Fig. 8 show the comparison of measured and modelled averaged (on one-hour basis) velocities during the period of analysis, at depths of 8 m, 22 m and 26 m, respectively.

As may be seen from the figures, the results of the model hydrodynamics (Mike 3fm) show adequate accuracy and are transferred into the velocities on open boundaries of the numerical model Mike 21fm.

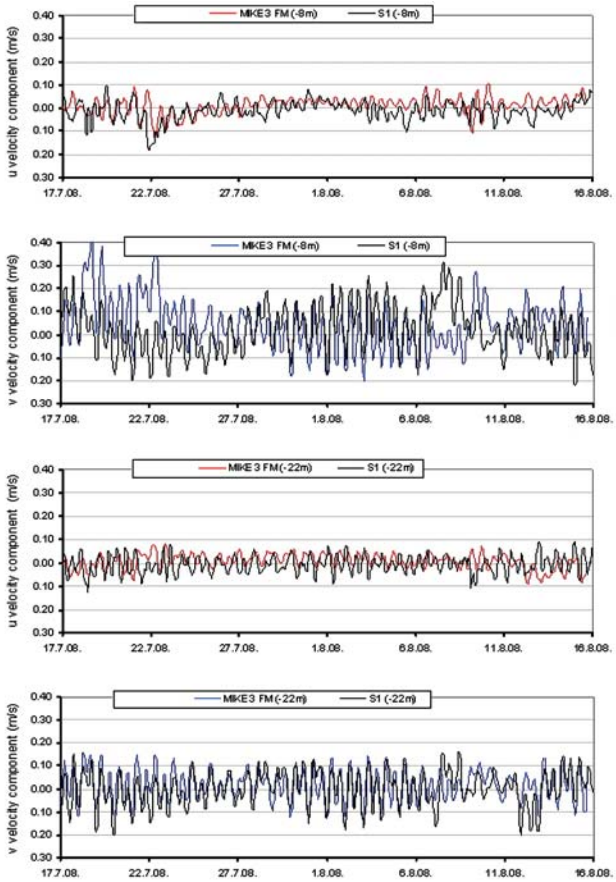

Figure 7 *Comparison of measured and modelled (Mike 3fm) averaged stream velocities at position of ACDP station S1 at depth of 8 and 22 m*
Slika 7. *Usporedba izmjerenih i modeliranih (Mike 3fm) osrednjenih brzina strujanja na položaju ADCP postaje S1 na 8 i 22 m dubine*

4 Results of numerical modeling
Rezultati numeričkog modeliranja

Fig. 9 shows averaged (on one hour basis) currents obtained with model Mike 21fm for several characteristic periods during the period of analysis.

In Fig. 9 (period 22.07.2008.) it is easy to notice the influence of wind (bora) which, in the initial period, directs surface stream from the coastal area towards the open sea. After that, (period 25.07, 2008.) a breakthrough of water from the open sea into the coastal zone takes place, with flow separation into northwest and southeast streams [25].

The two remaining periods (06.08.2008., 10 a.m. and 06.08.2008., 4 p.m.) are characterized by the calm, when more typical conditions of flow along the coast occurs, and direction changes are dominated by the tide signal.

Fig. 10 and Fig. 11 show the fields of averaged concentrations of faecal coliforms obtained in the model Mike 21fm, for the four periods shown above in Fig. 9. Fig 10 refers to the present status of development of public sewerage systems with mechanical pre-treatment, and Fig.

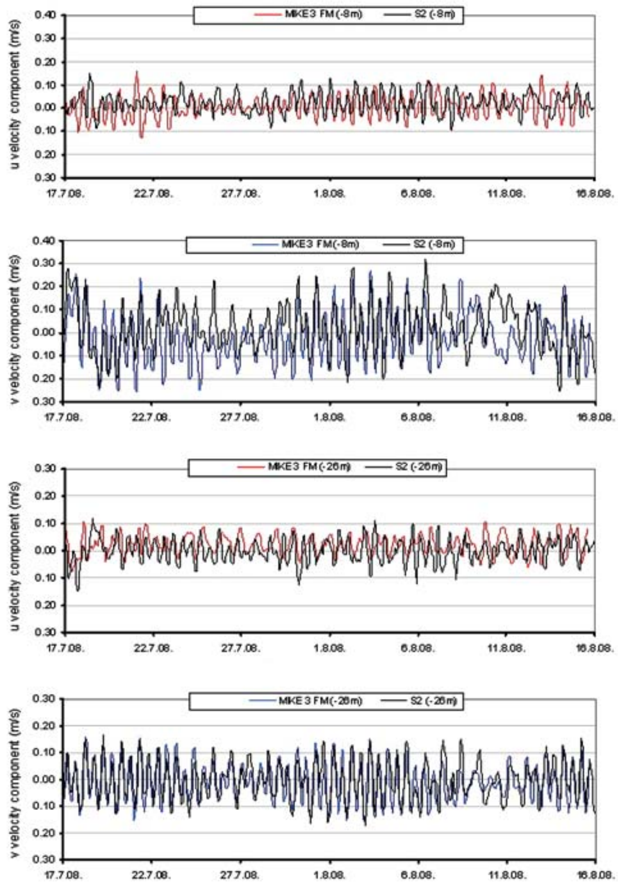

Figure 8 *Comparison of the measured and modelled (Mike 3fm) averaged stream velocities at position of ACDP station S2 at depth of 8 and 26 m*
Slika 8. *Usporedba izmjerenih i modeliranih (Mike 3fm) srednjenih brzina strujanja na položaju ADCP postaje S2 na 8 i 26 m dubine*

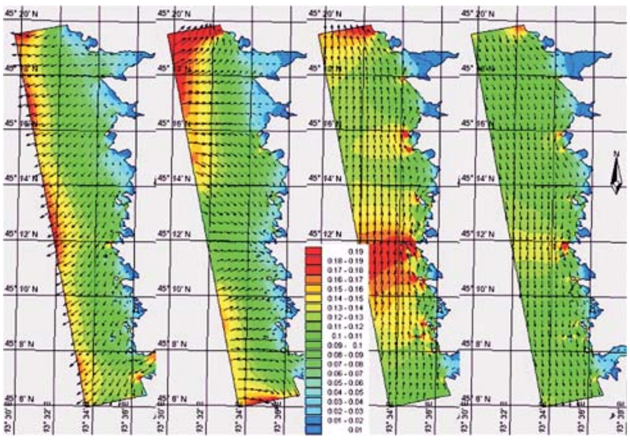

Figure 9 *Averaged stream fields obtained with model Mike 21fm in periods July 22, 2008, 3:00; July 25, 2008, 12:00; August 6, 2008, 10:00; August 6, 2008, 16:00 (from left to right)*
Slika 9. *Osrednjena polja strujanja dobivena modelom Mike 21fm u periodima 22.7.2008 3:00; 25.7.2008 12:00; 6.8.2008 10:00; 6.8.2008 16:00 (s lijeve na desnu stranu)*

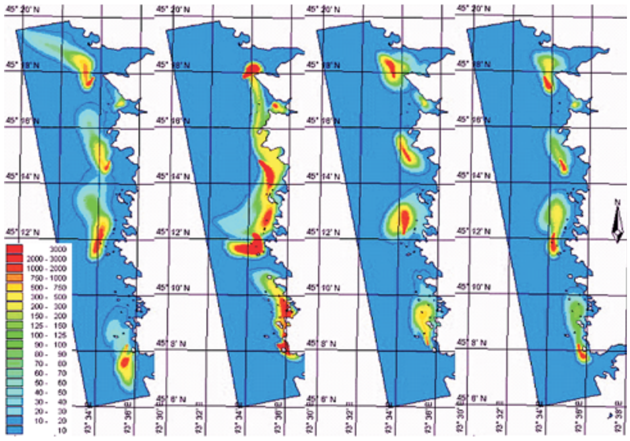

Figure 10 *Fields of averaged concentrations of faecal coliforms for present status of development of public sewerage systems (from left to right)*
Slika 10. *Polja osrednjenih koncentracija fekalnih koliforma za postojeće stanje izgrađenosti sustava javne odvodnje (s lijeve na desnu stranu)*

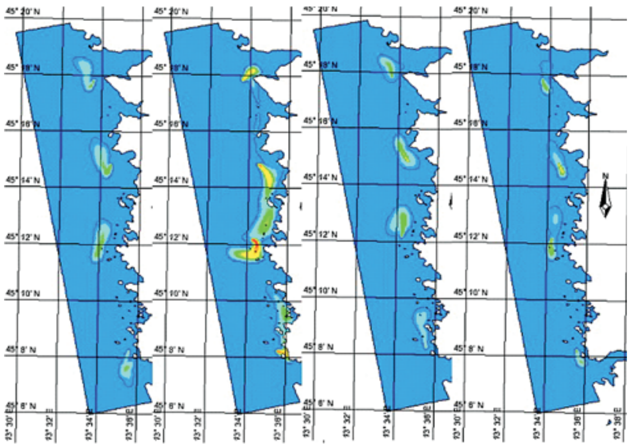

Figure 11 *Fields of averaged concentrations of faecal coliforms for planned level of development with use of membrane technology of treatment (from left to right)*
Slika 11. *Polja osrednjenih koncentracija fekalnih koliforma za planirano stanje izgrađenosti uz primjenu membranske tehnologije pročišćavanja (s lijeve na desnu stranu)*

11 to the planned level of development with the use of membrane technology as waste water treatment.

Fig. 12 shows the dynamics of concentration of faecal coliforms during the period of analysis at points 300 m away from the coast (Fig. 12 right) where by insight into the results of numerical analyses the occurrence of high concentration values was noticed at the present status of development. The comparison of dynamics indicates considerable reduction of FC concentrations in the zones designed for sports and recreation (zone 300 m from shore), provided the planned works include membrane technology treatment.

5 Conclusion
Zaključak

This paper shows the possibilities of applied numerical modelling for studies of pollution discharge in coastal zones. The value of the presented procedure is in the fact that it allows realistic representation of pollution discharge, and that it is the basis on which to reach the conclusions regarding defining an optimum strategy for environmental protection.

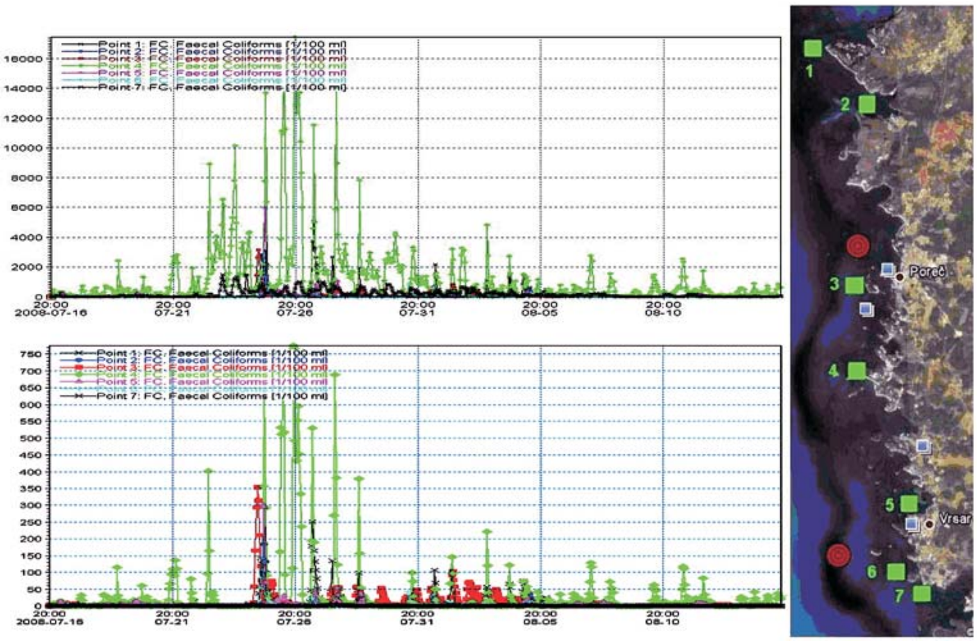

***Figure 12** Dynamics of concentration of faecal coliforms at points 300 m from shore (top left panel: present status of development, bottom left panel: planned level of development with use of membrane treatment technology, right panel: red - temperature and salinity measurement points; green - points 300 m from shore with highest concentration of faecal coliforms)*

***Slika 12.** Dinamika koncentracije fekalnih koliforma u točkama na 300 m od obale (gore: postojeće stanje izgrađenosti, dolje: planirano stanje izgrađenosti uz primjenu membranske tehnologije pročišćavanja, desno: crveno – mjerna mjesta temperature i saliniteta; zeleno – točke na 300 m od obale na kojima je zamiješena najveća koncentracija fekalnih koliforma)*

The actual example presents the results of numeric analyses of streams and dynamics of concentration of faecal coliforms in the wider coastal zone of Poreč. Comparing the influences of the present and the planned manner of waste water discharging from public sewerage (by submarine outfalls) it is possible to define the necessary level of wastewater treatment. The results indicate that the present status of development of sewerage systems in the Poreč area is inadequate as regards achieving the required results, and that it is necessary to apply a higher level of treatment.

The use of the described procedure of numerical modelling of pollution discharge in coastal zones should become a standard in defining and determining of the strategy of environmental protection, regardless of whether the problems are solved at the local or the regional level.

6 References
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